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Investigating Power System Primary and Secondary Reserve Interaction under High Wind Power Penetration Using Frequency Response Model

J. TAN,[a] Y. ZHANG,[a,*] I. KRAD,[a] V. GEVORGIAN,[a] E. ELA[b]
[a] National Renewable Energy Laboratory
[b] Electric Power Research Institute
USA

SUMMARY

Power system frequency needs to be maintained close to its nominal value at all times to avoid machine damage, under-frequency load-shedding and even blackouts. Adequate primary frequency response and secondary frequency response are the primary forces to correct an energy imbalance at the second to minute level. As wind energy becomes a larger portion of the world's energy portfolio, there are greater oppotunities for wind to provide frequency response services. This paper addresses one area of frequency control that has been missing in previous work – the reliabilty impacts and interactions between primary and secondary frequency control. The lack of a commercially available tools to simulate the interaction of these two responses has limited the energy industry's understanding of when the depletion of primary control reserve will impact the performance of secondary conrol response or vice versa. To investigate this issue, in this paper we develop a multi-area frequency response integration model with combined primary and secondary frequency control capabilities.

KEYWORDS

Frequency response, primary reserve, secondary reserve, automatic generation control, energy scheduling, power system reliability

I INTRODUCTION

To successfully manage the nation's bulk electric power system, the balance between generation and load must be maintained at all timescales. The timescale at which this occurs will dictate the operation needed to ensure that the system is in balance. An imbalance between generation and load can overload transmission lines and cause unscheduled power flows, voltage magnitude fluctuations and electrical frequency deviations. A severe frequency deviation can lead to a partial system failure or worse, a cascading failure (e.g. blackout). Electric power system operators use a variety of scheduling techniques to maintain the electricity frequency close to its nominal value at all times. An interconnected power system must have adequate resources to respond to a variety of contingency

* yingchen.zhang@nrel.gov

events to ensure rapid restoration of the frequency. Primary frequency response (PFR)—also called primary control reserve [1] and frequency responsive reserve [2]—is the capacity available for automatic local response to frequency excursions through turbine speed that adjusts to counter-frequency deviations to stabilize the frequency [3]. PFR occurs shortly after an event and acts to stabilize the frequency deviation to a steady-state level. While primary control is a function of local controllers responding to frequency deviation, secondary freqeuency response (SFR) control is a centralized control directed by the system operator. It utilizes automatic generation control (AGC) to restore the system frequency to its nominal value and keep the scheduled interchanges between balancing areas to their scheduled level.

Wind power has the capability to provide both forms of responses through active power control. To provide upward reponse due to under-frequency conditions, wind power plants needs track its maximum available power and scheduled their output below their maximum power point [4]. This is different from conventional generators, which can increase or decrease their fuel flow to control their power output willingly. With increased wind power penetration in all major North American interconnections, it is desired to expand the use of frequency control capabilities that can be provided by wind technology [5]. If designed correctly, active power control from wind can have superior performance compared to conventional generators in terms of speed and accuracy, because most existing wind power plants interface with power grids through power electronics devices [6].

One of the challenges of using wind power for frequency regulation is the unknown outcome when primary and secondary reserves interact [5]. In current system operations, PFR reserve is not scheduled in unit commitment and real-time dispatch, because it is assumed as an inherent function of conventional generators (direct control over fuel flows through steam valve, gate valve, or combustor) and that there is always ample supply. However, with increased penetration of wind, this may not always be the case. Under current operating mechanisms, if wind power is enabled to provide both primary and secondary responses but only secondary reserve is scheduled through the ancillary service market, if an event happens that deployes PFR reserves, there will be a deficiency on the energy that restores the system frequency response to its nominal value. Also, under circumstances in which the secondary reserve is under-procured, primary response will automatically act to further restore frequency. As a result, the remaining primary response may not be available to stabilize frequency after a sudden loss of generation.

Mitigating these challenges requires a tool that can realistically model the interactions between primary and secondary control. There are tools that are designed to implement AGC in an extended system simulation. For example, the Power System Simulator for Engineering (PSS®E) is a software tool that simulates power system steady state and dynamic performance. In 2011, PSS®E rolled out a new function called "extended term dynamic simulation," which extended the time frame for dynamic simulation to virtually unlimited and implemented slow-moving controls, such as AGC, switched shunts, and transformer tap changing [7][8]. PSS®E uses implicit integration to solve differential equations with changing time steps. This function offers means to change simulation time steps by choosing different modes; however, when the user choses large time steps, the fast responses will be filtered. The unit allocation is calculated using unit base point, unit maximum regulation, and the ramp rate.

KEMA, Inc., published the Renewable Energy Modeling and Integration Tool (KERMIT) [9] to simulate power system frequency behavior during 24 hours. The tool incorporates an AGC model that responds to non-fault events, such as a generator trip, load shedding, and variation of renewable resources. The major drawback is that KERMIT does not include a detailed network model. The inter-area flows are calculated by relative phase angles between areas. As a result, KERMIT does not have individual dynamic responses for each generator. KERMIT was utilized to study the impact of renewable generation on the California grid [10] [11]. A similar study was done on the PJM grid to assess the effectiveness of AGC in a frequency regulation market [12]. All of the KERMIT-related studies focused on secondary reserves and AGC control without a balanced focus on PFR.

In this study, we address this challenge by designing a Multi-Area Frequency Response Integration Model (MAFRIM) in Simulink and using the Flexible Energy Scheduling Tool for Integrating Variable Generation (FESTIV) to provide economical scheduling. In the MAFRIM, we model a power system that has multiple balancing areas, and calculate the area control error (ACE) based on each areas' frequency deviation and tie-line flow deviation from scheduling. We decide the AGC participation factors based on economic reallocation from FESTIV scheduling. FESTIV is a forward-looking, electricity scheduling simulation software developed by NREL researchers. It includes security-constrained unit commitment, security-constrained economic dispatch, and AGC sub-models. Each sub-model's output serves as the input to subsequent sub-models [14]. The over all structure of the proposed tool and methodology are displayed in Figure 1.

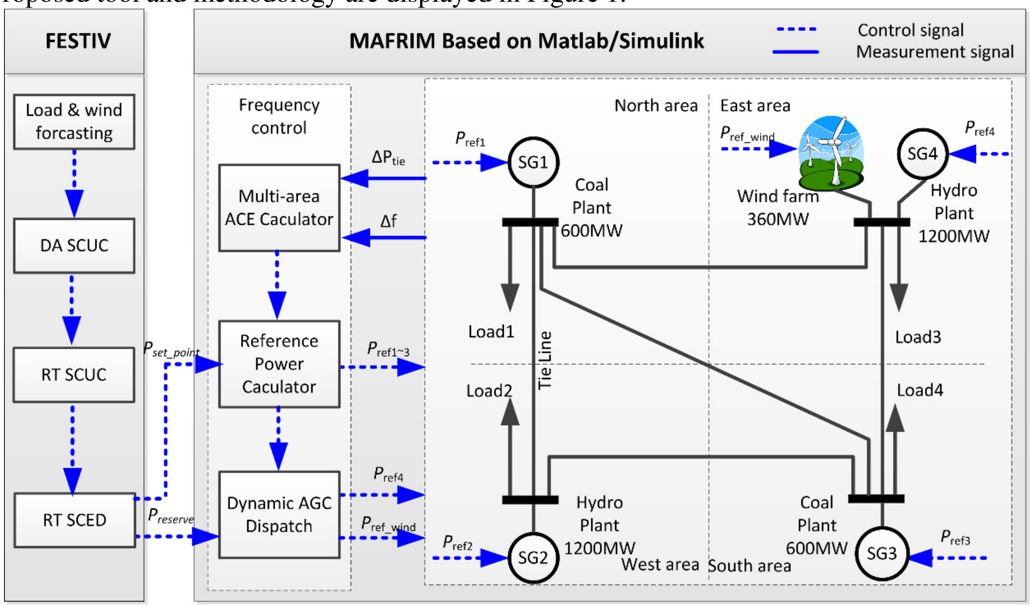

Figure 1. Four-area, four-generator system

Section II describes the model development and validation. Section III and IV provide case studies on the interactions between wind primary and secondary reserves. Section V provides a discussion and conclusion.

II MODEL DEVELOPMENT AND VALIDATION

MAFRIM integrates PFR (turbine governor control) with secondary frequency response (AGC). It simulates the power system dynamic response in a full time spectrum with variable time steps, from milliseconds to minutes and hours to days. It is capable of simulating both normal and event conditions, and it can represent real power system operations and thus evaluate the adequacy of primary and secondary reserves. This unique interaction between a turbine governor model and a novel AGC model places special emphasis on electric power systems that have high penetrations of wind generation. To ensure the credibility of the model, a demonstration model provided by GE's Positive Sequence Load Flow (PSLF) dynamic simulation software is used and translated into the Simulink platform. The model configuration is displayed in Figure 1. The dynamic model of MAFRIM has been validated against the PSLF simulation, and the results are displayed in Figure 2 and Figure 3. Figure 2 shows the rotor speed and real power output of all the generators after a sudden load shedding. Figure 3 shows the terminal voltage magnitude of all of the generators after a fault. The performance of the Simulink model closely matches the results of the PSLF simulation.
In addition to the validated dynamic model, an AGC controller is modeled in Simulink. The ACE calculation of the AGC controller is discribed below.

$ACE_i = \Delta P_{tie,i} + \beta_i \Delta f_i,\quad \Delta P_{tie,i} = \sum_{\substack{j=1 \\ j\neq i}}^{N} \Delta P_{tie,ij} = \frac{2\pi}{s}\left[\sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij}\Delta f_i - \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij}\Delta f_j\right]$, where β_i is a bias factor of area i, $\Delta P_{tie,i}$ is the tie-line power change of area i, Δf_i is the frequency deviation of area i, and T_{ij} is the synchronizing torque coefficient between areas i and j.
Finally, a Type 3, 360-MW wind turbine plant model [13] is added in area 4.

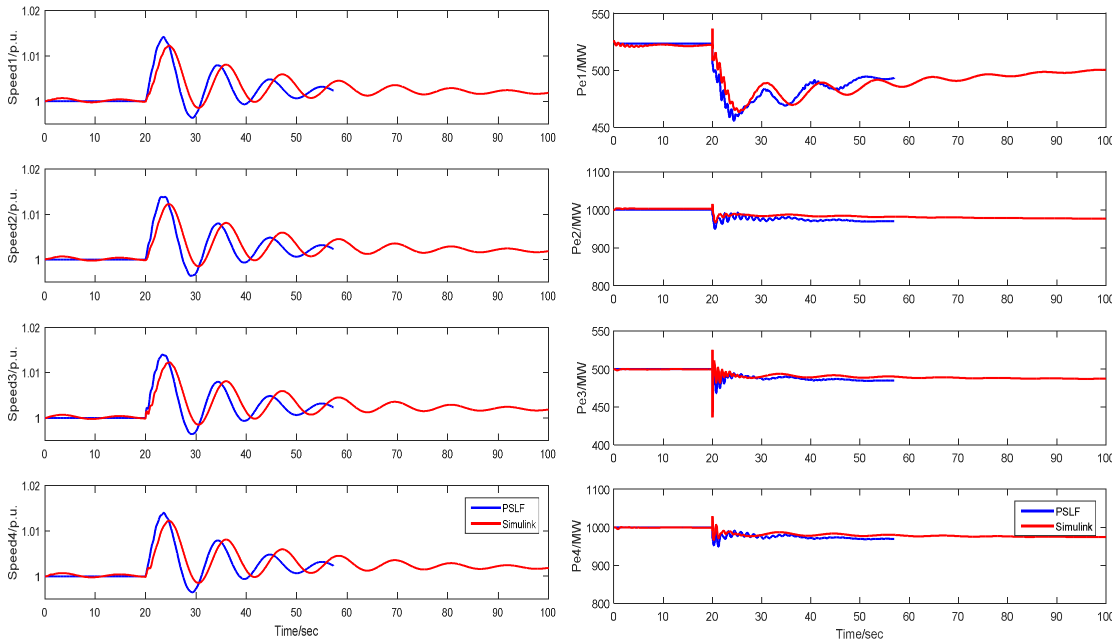

Figure 2. Comparaison of rotor speed and active power of all generators in PSLF and Simulink

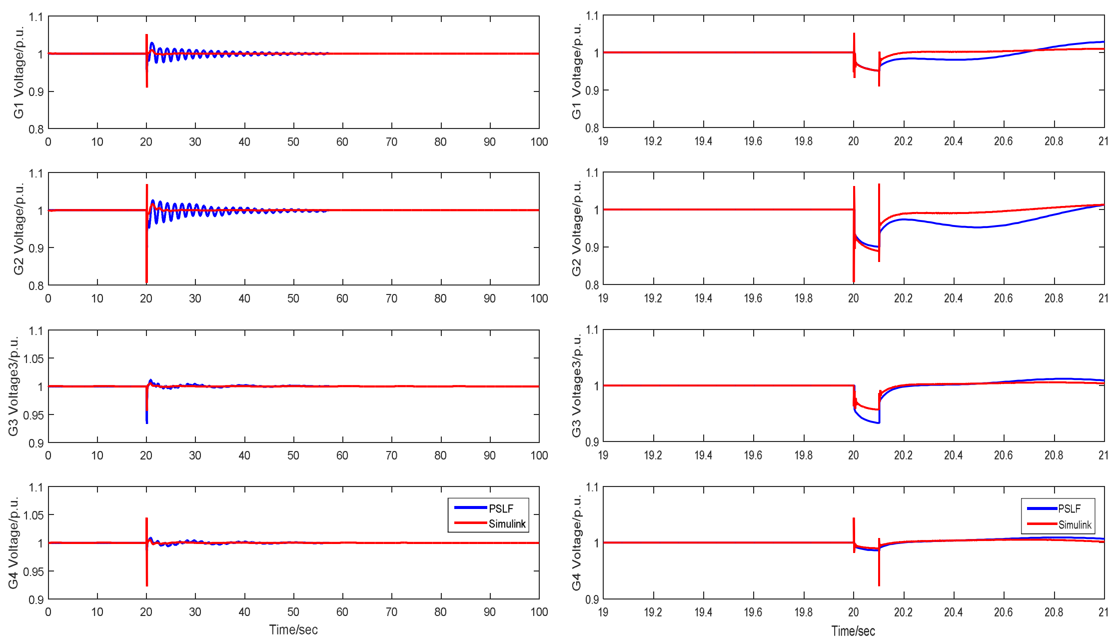

Figure 3. Comparaison of terminal voltages (zoom in on the right) of all generators in PSLF and Simulink

III CASE STUDIES

The purpose of this study is to investigate the interaction of the primary and secondary reserves using MAFRIM. The credibility of the accuracy of the MAFRIM simulation lies in the dynamic model benchmarking using PSLF, as discussed above. It also lies in the natural connection to the energy scheduling tool FESTIV. This study uses FESTIV to generate 24-hour schedules for all generators in MAFRIM. All generators are enabled to schedule regulation reserve. The scheduling assumes no forecasting errors for wind power.

The 24-hour simulation results are displayed in Figure 4. The load profile displayed is the aggregate of all loads at different parts of the system. The generators respond to load changes by following the 5-

minute energy scheduling and 4-second AGC; therefore, their outputs deviate from the energy scheduling when providing either PFR or SFR. Wind generator output is also limited by its maximum power point tracking. This 24-hour simulation does not include any disturbances. All the frequency deviation is caused by load ramping and the quick response of wind to the dispatch signals. In reality, system operators manually impose ramp limiter on wind power plants to decrease frequency volatility caused by their quick response. In this study, ramp limiters are not considered.

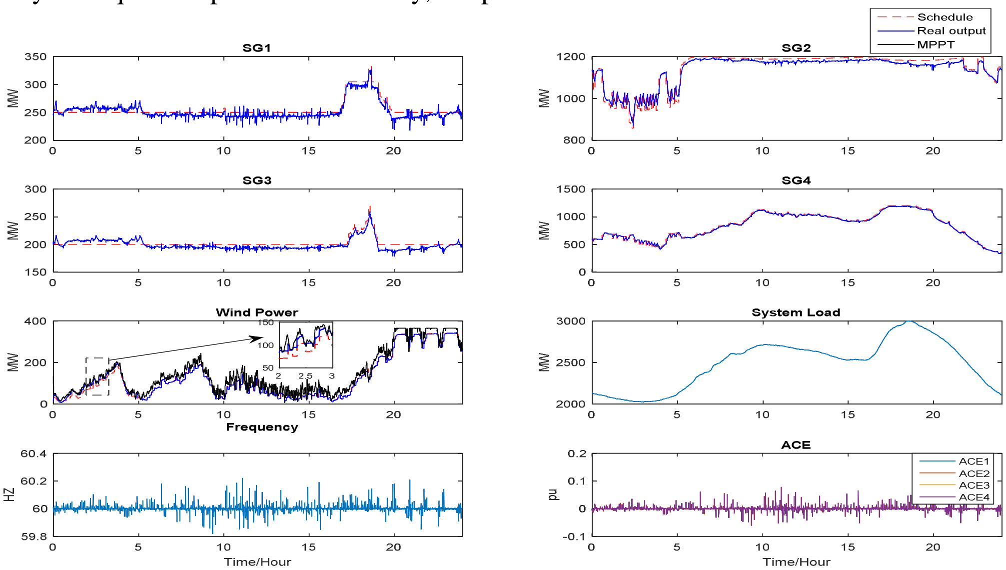

Figure 4. Scheduling (FESTIV) and real output (MAFRIM) of generators for 24 hours, system load, frequency, and area control error

IV RESULTS

To study the interaction between primary and secondary reserves, we applied disturbances at different times during the 24-hour simulation. The primary focus is to assess the frequency response when wind generators are providing PFR, AGC, or both. Figure 5(a) illusrates that when wind is providing SFR and an event happens, wind does not have enough headroom to provide a full-scale PFR. Wind that provides only primary response has a better frequency nadir. Wind that provides only AGC has a faster response to restore frequency.

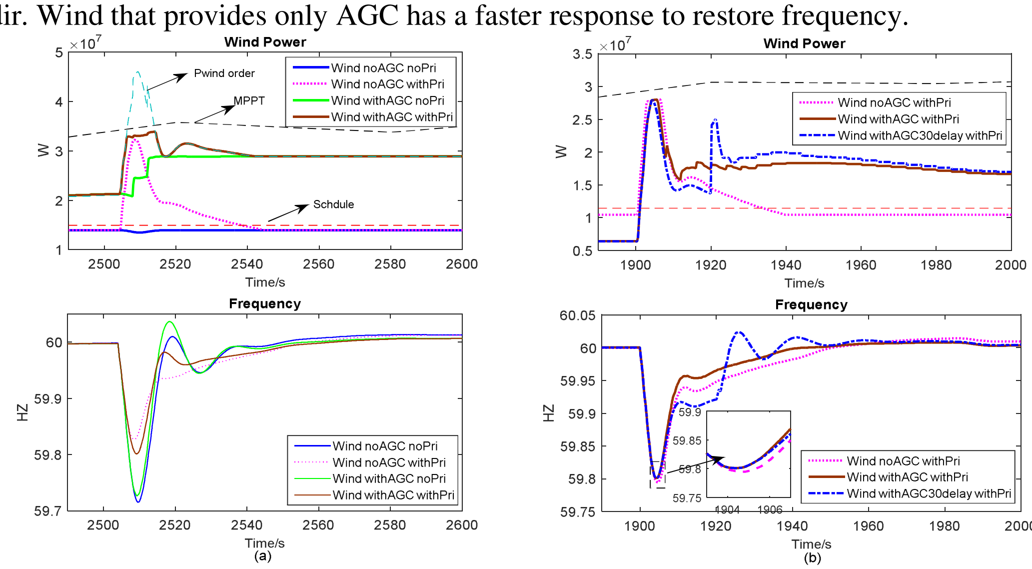

Figure 5. (a) Wind power and system frequency when load increases 50MW at t=2504s (b) Wind power and system frequency when load increases 50MW at t=1900s

In most system operations, the AGC signal is disabled for tens of seconds immediately following a disturbance, so that the controllers can focus on stablizing the system to equilibrium. We simulated that effect by disabling AGC for 30 seconds after the disturbance occured, as shown in Figure 5(b). Also, in this case, when the disturbance happens, the wind power plant has enough energy to provide both primary and secondary response in full scale. The result shows that the the frequency nadirs for delayed and non-delayed AGC response are nearly the same. When the wind's maximum power has enough room for both primary and secondary reserves, the frequency nadir will be higher, and the restoration time will be shorter.

V CONCLUSION

The proposed tool allows developing better understanding of the interaction between PFR and SFR, which are responses typically simulated with separate tools. An improved understanding of the interactions of these controls should be sought so that any reliability issues that occur between the seams of these two timeframes can be assessed. Careful consideration of these interactions will improve power system reliability, and help in the designing of control systems that will result in responses that are in many ways superior to those of conventional thermal generation, all while resulting in very little effect on the loading and life of the wind turbine and its components. Better understanding of the interaction between primary and secondary frequency control on multi-area systems with and without wind power plants providing both of these controls, and how it impacts reliability compliance measures in various grids will help industry to move forward on PFR market designs.

BIBLIOGRAPHY

[1] ENTSO-E, UCTE, *Operational Handbook Policy 1: Load-Frequency Control and Performance* (Brussels, Belgium, March 2009).

[2] Western Electricity Coordinating Council, "White Paper on Frequency Responsive Reserve Standard" (April 2005).

[3] N. Miller et. al., "California ISO Frequency Response Study" (Final Draft), (Schenectady, NY: GE, November 2011).

[4] J. Aho et. al., "Controlling Wind Turbines for Secondary Frequency Regulation: An Analysis of AGC Capabilities Under New Performance Based Compensation Policy," in the *13th International Workshop on Large-Scale Integration of Wind Power Into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants Proceedings* (Berlin, Germany, November 2014).

[5] J. H. Eto et. al., *Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation* (Technical Report) (Berkeley, CA: Ernest Orlando Lawrence Berkeley National Laboratory, December 2010).

[6] E. Ela et. al., *Active Power Controls from Wind Power: Bridging the Gaps* (Technical Report), NREL/TP-5D00-60574 (Golden, CO: January 2014).

[7] L. Wang and D. Chen, "Automatic Generation Control (AGC) Dynamic Simulation in PSSE," *Power Technology* (February 2011). w3.usa.siemens.com.

[8] L. Wang and D. Chen, "Experience with Automatic Generation Control (AGC) Dynamic Simulation in PSSE," *Power Technology* (August 2012). w3.usa.siemens.com.

[9] "KERMIT Dynamic Models," KERMIT Documentation for CA ISO Training.

[10] KEMA, Inc., *Research Evaluation of Wind Generation, Solar Generation, and Storage Impact on the California Grid* (Project Report) (Sacramento, CA: California Energy Commission, June 2010).

[11] KEMA, Inc., *Emission II Study of Advanced Storage used for Frequency Regulation* (Technical Report) (Albuquerque, NM: Sandia National Laboratories, December 2012).

[12] KEMA, Inc., *KERMIT Study Report: To Determine the Effectiveness of the AGC in Controlling Fast and Conventional Resources in the PJM Frequency Regulation Market* (Technical Report) (Norristown, PA: PJM, December 2011).

[13] E. Ela et. al, *Active Power Control from Wind Power phase 1 Report* (Technical Report) (Golden, CO:)

[14] E. Ela et. al., "A Flexible Power System Operations Simulation Model for Assessing Wind Integration," in *IEEE Power and Energy Society General Meeting Prcoeedings* (Detroit, MI: July 2011).